PROGRESS REPORT FORM   Grant No. DE-FG02-90ER61064

1.   PI and Co-I Names and Affiliations

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2.   Title of Research Grant

Radiative Transfer for Clear and Cloudy Atmospheres: Spectral Modeling and Validation

3.   Scientific Goal(s) of Research Grant

A principal objective of this research effort is to develop radiative transfer models for utilization by ARM scientists and by the broader community, including those involved with GCMs. We view that one aspect of our responsibilities is to provide a link from sources of relevant data, both laboratory- and field-generated, to the atmospheric radiation transfer community, primarily through our continued development of the line-by-line model LBLRTM and the CKD continuum. A central feature of the suite of models developed under this grant is the role played by ARM data. This includes the use of ARM data for both the development and validation of the models. The models fall into two principal categories: 1) Highly accurate spectral models and 2) more efficient band models appropriate to implementation in GCMs. Our objective is to develop rapid models which provide results (e.g., cooling rates) that are essentially the same as those from the reference models which have been validated with ARM data but with acceptable computational cost.

4.   Accomplishments

• measurement/model comparisons in shortwave - paper accepted in GRL concerning comparisons between RSS direct and diffuse irradiance measurements and corresponding calculations by CHARTS.   Three important conclusions: a) there is no significant absorption by unmodeled gases; b) measurement/model agreement for diffuse irradiances requires lower aerosol single scatter albedos than typically assumed; and c) standard extraterrestrial solar source functions (based on Labs & Neckel) not consistent in all spectral regions with corresponding values derived based on lamp calibrations.

• broadband QME - a Quality Measurement Experiment has been initiated to compare broadband pyrgeometer measurements, AERI 'derived' fluxes, LBLRTM 'derived' fluxes, and RRTM-calculated fluxes. The results of this QME have indicated that the pygeometer fluxes agree to 5-10 W/m2 with the other fluxes.

• longwave RRTM - RRTM has been chosen as the official longwave radiation transfer code in the ECMWF operational forecast model and is being used in the ECMWF 40-year reanalysis.

• cloud overlap in RRTM - the novel maximum-random cloud overlap method developed for RRTM has been evaluated (and subsequently incorporated) in the version of RRTM used at ECMWF.

• shortwave RRTM - a collaboration with ECMWF has begun in which the flux and cooling rate calculations of the shortwave version of RRTM are used to improve the ECMWF shortwave model, which can be in error by as much as 30 W/m2.

• improvements associated with LBLRTM - modifications to the CKD continuum has been implemented for water vapor, nitrogen, and collision induced oxygen bands from the 1600 cm-1 to the mid visible. Improved line parameters have been incorporated, most

notably for water vapor (Toth and Brown in infrared; Giver et al. in the visible and near infrared).

• MonoRTM - this model, designed to perform radiative transfer for limited number of spectral elements, has been completed and will be used in the retrieval of precipitable water vapor and cloud liquid water.

• Analysis of MWR measurements - the improvements in the AERI/LBLRTM QME as a result of scaling sonde water vapor profiles to agree with MWR column amounts continue to be actively monitored. The relative contributions in the microwave of the foreign and self continua remains an active area of investigation (see Figure 1).

5.   Progress and accomplishments during last twelve months

A key accomplishment of our research under this grant during the past year is the completion of a study comparing RSS direct and diffuse measurements of solar irradiance with corresponding radiative transfer calculations by CHARTS, and the authorship and subsequent acceptance by GRL of a paper detailing our results. We regard our solar paper ("Comparison of spectral direct and diffuse solar irradiance measurements and calculations for cloud-free conditions", by Mlawer et al.) as being particularly important in establishing, in light of recent papers suggesting the existence of clear-sky solar 'anomalous' absorption, the current modeling capability for the clear sky with aerosols included. The ability to achieve these results is a direct consequence of the quality of the RSS measurements. Two critical aspects of the instrument in addition to the spectral resolution capability are (i) that the direct and diffuse irradiances are measured concurrently, enabling the aerosol single scatter albedo to be inferred, and (ii) the photometric calibration of the instrument. The implementation of downward looking MFRSR at the CART site was important for an approximate spectral representation of the surface albedo.

There are a number of notable conclusions from the study. For energy balance issues, the molecular absorption is adequately described with the current line parameters (including water vapor lines and continuum, oxygen lines and collision induced oxygen, and ozone). The values for the single scattering albedo for the cases studied range lower than those generally used by the aerosol community. The Kurucz solar source function, which uses the measurements of Labs and Neckel to establish its broadband distribution, provides an excellent (though not perfect) representation of the solar function at high resolution. There is clear evidence from this work and the work by Harrison and Michalsky that there is a discrepancy between the extraterrestrial spectrum derived from Langley analyses with NIST standard lamp calibrated RSS measurements and that given by the Kurucz (and by extension Labs and Neckel) and WMO solar spectra. The discrepancy has a spectral dependence ranging from 1% to 5% at the shorter wavelengths, amounting to ~20 W/m^2. It is of interest that this discrepancy is of similar magnitude to that obtained for the calibration of the NASA satellite instruments. A method of analysis has been used in our study so that the results are not dependent on this discrepancy.

This analysis convincingly demonstrates that the same type of QME analysis is appropriate for the solar regime as has been implemented in the thermal regime. The measurement and modeling capabilities are sufficiently stable so that Langley regressions are not required. A quasi QME has been initiated (the atmospheric state used is identical to that used for the longwave QME) in the sense that many more cases are in the process of being run. Unfortunately, this is not possible in an automated manner, principally because the RSS data is not available in the archive.

The Angstrom relation used to model the spectral characteristics of the aerosol extinction in the spectral domain of the RSS is remarkably effective for the cases studied.

As for our research efforts related to radiative transfer modeling appropriate for use in climate models, we are happy to report that the RRTM has been adopted as the official longwave scheme at ECMWF. This means that RRTM will be used in the ECMWF operational forecast model (TL319 L60), in the ECMWF 40-year reanalysis (ERA-40), as part of the ensemble forecast system (51x10-day forecasts at TL159 L40 every day), and in the experimental seasonal forecasts (ensemble of 3 TL159 L40 4- to 6-month simulations run every week). It is important to note that this accomplishment has been achieved due to the efforts of many in the ARM community, especially members of the IRF working group. We regard RRTM as the vehicle by which it has been possible to transition the results from ARM, particularly the measurement results, into the GCM community. The most effective ARM effort in this regard has been the AERI/LBLRTM QME.

A new collaboration with ECMWF has been started to improve the ECMWF shortwave model. Due to computational cost constraints, RRTM_SW is not presently a candidate for implementation in the GCM. However, it is the objective of our collaborative effort to modify the ECMWF shortwave model to provide results much closer to those from RRTM_SW (with DISORT) than is currently the case.

In additional, the k-distributions developed for RRTM in the shortwave have been incorporated into the 3d radiative transfer model SHDOM.

A new Quality Measurement Experiment, focused on longwave broadband measurements and calculations, has been initiated during the past year. This effort has been motivated by the realization that many scientists in the GCM community are more persuaded by broadband

model/measurement validations for flux than by comparisons associated with spectral radiances. This QME involves the following components:

   a) Surface and TOA RRTM radiances for zenith angle of 0 by RRTM spectral band and total.

   b) Extension of the AERI downwelling spectral radiance measurement from 550 cm-1 to 500 cm-1using the LBLRTM calculation.

   c) Surface AERI radiances by RRTM spectral band and total.

   d) RRTM fluxes and cooling rates at all model levels by spectral band and total.

   e) Derived AERI downwelling flux: spectral (10 cm-1), by RRTM band, and total.

   f) Derived LBLRTM downwelling flux: spectral (10 cm-1), by RRTM band, and total.

   g) Broadband Pyrgeometer measurements.

'Derived' in our approach utilizes a theoretical radiance to flux conversion based on the optical depth at each AERI/LBLRTM spectral element. The atmosphere is characterized as a single layer except for the principal ozone band for which two layers are used. A renormalization is performed on the AERI and LBLRTM 10 cm-1 results to ensure that the flux from radiance conversion for AERI and LBLRTM is identical to that for RRTM (obtained using first moment quadrature with 6 streams).

This QME enables the comparison of the broadband pyrgeometer results with the derived AERI and LBLRTM fluxes. It enables the comparison of the results from other RT models with the AERI and LBLRTM results by integrating the 10 cm-1 spectral fluxes over the spectral bands of the relevant model. The QME has been applied to part of the Sept 97 IOP (and to a period of interest in Sept 99) for studying the performance of an extended set of pyrgeometers including a scanning pyrgeometer. The initial results, as shown in Figure 2, are consistent with previous analyses of SFC fluxes inferred from the AERI measurements.

With IRF input, the input files for the radiative transfer calculations have been improved. Two LBLRTM runs are now performed: i) one with the sonde input profile scaled to the MWR water vapor column and ii) one modeling the transition region from the interferometer to the first atmospheric level. The AERI measurement is modeled with the proper combination of these two results. This approach will be used for the standard AERI/LBLRTM QME as well as for this Broadband LW QME. The ozone profile is now being scaled to provide agreement with TOMS measured column.

Improvements related to atmospheric radiative transfer modeling, and LBLRTM in particular, are ongoing. Significant improvements have been implemented in the continuum model used in LBLRTM, including modifications for water vapor, nitrogen and a number of collision induced oxygen bands from the 1600 cm-1 to the mid visible. In addition, efforts have continued this past year to revise the lineshape formulation on which the CKD water vapor continuum is based to one in which collision-induced transitions are the dominant continuum absorber at band center. The line parameters are continuing to be updated on the basis of collaborative research efforts. The principal improvements have been for water vapor in the infrared due to Toth and Brown at JPL and in the visible and near infrared by Giver and his colleagues at NASA Ames.

Lastly, we have initiated a collaboration with the SCM working group to transition radiative improvements developed in the IRF to the radiative transfer models being used by SCM models. In particular a standard flux and cooling rate product is being developed for the SCM through a collaboration with Ric Cederwall and Steve Krueger. A random cloud overlap approach is available for the approach in which a single column calculation is to be used for the SCM grid box.

MWR 23.8 GHz Brightness Temperature Fitted with Simple Linear Model
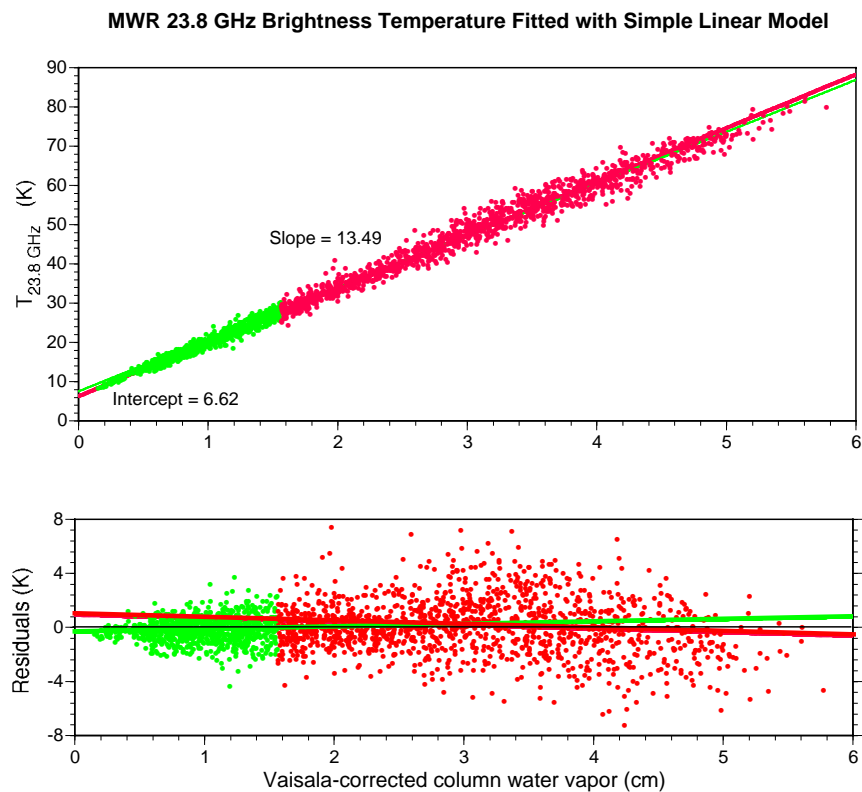

Figure 1. A linear relationship between the 23.8 GHz brightness temperature and the column water vapor (top), the slope of which is dependent on the foreign water vapor continuum, leaves a residual (bottom) that is dependent on the column amount and is related to the contribution from the self continuum. (S.A. Clough, AER Inc., 1999)
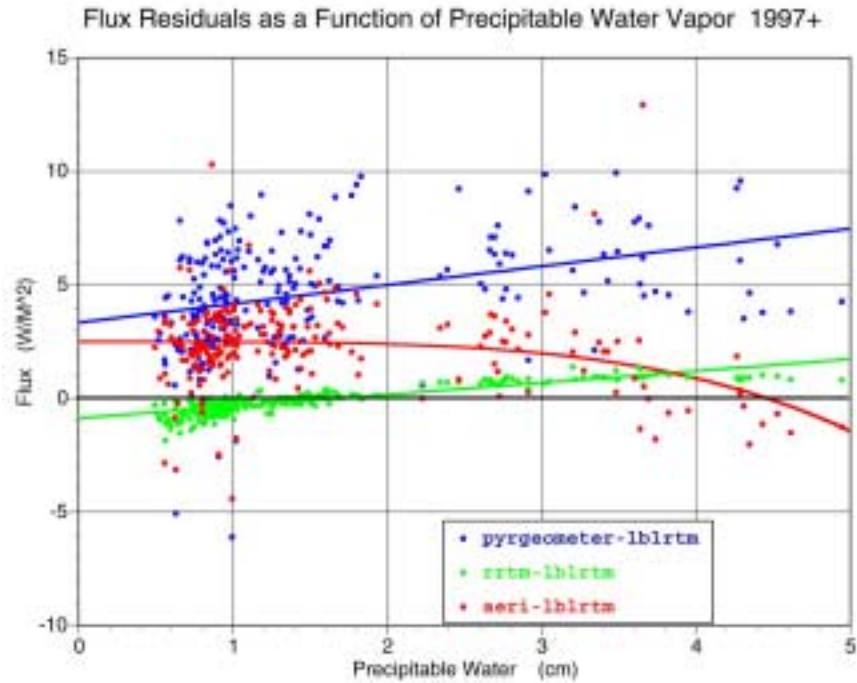
Figure 2. Longwave broadband QME results for September 1997 IOP. (S. Clough, AER, Inc., 1999)

6.   Electronic figures.

See above.

7.   Refereed publications submitted or published during the *current* grant FY.

Mlawer, E.J., P.D. Brown, S.A. Clough, L.C. Harrison, J.J. Michalsky, P.W. Kiedron, and T. Shippert, Comparison of spectral direct and diffuse solar irradiance measurements and calculations for cloud-free conditions, *Geophys. Res. Lett.*, in press.

(under separate ARM grant)

Iacono, M.J., E.J. Mlawer, S.A. Clough, and J.-J. Morcrette, Impact of an improved longwave radiation model, RRTM, on the energy budget and thermodynamic properties of the NCAR community climate model, CCM3. *J. Geophys. Res.*, 105, 14,873-14,890, 2000.

8.   Extended abstracts in the current FY.

McFarlane, S.A., K.F. Evans, E.J. Mlawer, and E.E. Clothiaux, Shortwave flux closure experiments at Nauru, in Proceedings of the Tenth Annual ARM Science Team Meeting, San Antonio, Texas, March 2000.

The extended abstracts associated with our other (6) posters at the 2000 ARM Science Team meeting are being completed.

9.   Status of submitted referred publications from the previous FY progress report.

NONE